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PROJECT ADMINISTRATION DATA SHEET

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Sponsor: University of Houston; Central Campus; Houston, Texas 77004

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Title: Design of a Vortex - Flow Solar Chemical Reactor

ADMINISTRATIVE DATA OCA Contact Duane Hutchison x4820

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Defense Priority Rating: None Security Classification: None

RESTRICTIONS

See Attached Government Supplemental Information Sheet for Additional Requirements.

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FORM OCA 4:781

GEORGIA INSTITUTE OF TECHNOLOGY — OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION SHEET

Date 3/12/82

Project Title: Design of a Vortex-Flow Star Chemical Reactor

Project No: A-3033

Project Director: Dr. Steve H. Bomar, Jr.

Sponsor: University of Houston

Effective Termination Date: 12/31/81

Clearance of Accounting Charges: ______

Grant/Contract Closeout Actions Remaining:

- [x] Final Invoice and Closing Documents
- [ ] Final Fiscal Report
- [ ] Final Report of Inventions
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FORM OCA 10:781

A-3033

FINAL TECHNICAL REPORT

DESIGN OF A VORTEX-FLOW SOLAR CHEMICAL REACTOR

By

Hampton L. Teague
Steve H. Bomar, Jr.

For

Solar Thermal Test Facilities
Users Association

Contracting Through

University of Houston
Houston, Texas 77004

Purchase Order No. 1-16302

GEORGIA INSTITUTE OF TECHNOLOGY
Engineering Experiment Station
Atlanta, Georgia 30332

Georgia Tech Project A-3033

December 1981

ABSTRACT

The purpose of this study, sponsored by the STTF Users Association, was to conduct a preliminary investigation of a vortex-flow chemical reactor, fired by concentrated solar radiation. The reactor would be capable of containing gaseous and solid particle reactants in the presence of high-flux radiant thermal energy, leading to chemical reactions which store solar process energy in chemical bonds.

The vortex-flow reactor concept appears to offer important technical advantages in process control, compared with other methods such as fluidized beds. Specifically, the flow rates of the entraining gases and the reactant gases can be varied independently in response to changes in power level caused by variations in solar intensity.

A model vortex-flow reactor was constructed and operated to determine its control characteristics at room temperature. A preliminary design was developed for a reactor suitable for testing at the DOE Advanced Components Test Facility.

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A. Objectives

The objectives of this project were to:

1. Investigate the fluid flow characteristics of a bench scale vortex-flow solar chemical reactor simulator,

2. Identify optimum dimensional ratios and equipment arrangements for future scale-up and construction of a working vortex-flow reactor system for testing at the DOE, Advanced Components Test Facility,

3. Generate design sketches and preliminary design data.

B. Background

If solar thermal technology is to be used for the production of fuels and chemical feedstocks, it is necessary that we develop chemical reactor designs capable of operating in the peculiar environments of solar thermal facilities. It seems reasonable to try to exploit the capability of solar thermal facilities to provide direct interaction between the reacting species and the high-flux radiant energy field. This demands that we develop reactor configurations and window materials to meet these requirements.

Several solar chemical reactor investigators have pursued concepts in which solid particles are suspended in streams of flowing gases. This approach gives excellent conditions for interaction of the reactants with the radiant energy field and corresponding uniform reaction temperatures throughout the reactor volume.

In a gas-solid reactor of this kind, however, some specified gas velocity is needed to maintain proper particle entrainment; this velocity is independent of the radiant thermal power input. Simultaneously, the rate of introducing reactant materials is very dependent on the radiant thermal power input. Thus, it is necessary to provide means of controlling the "particle-entraining" gas flows and the "reacting" gas flows independently of one another. The problem is illustrated by the tendency of a fluidized bed to run cooler than desired at low power input levels; if the reactant gas is kept flowing at a range sufficient to fluidize the bed, the low input power level causes a drop in bed temperature. In order to provide for independent control of entraining gas velocities and reactant gas flow rates, the vortex reactor should employ an externally driven blower.

An induced or "standing" vortex inside a reactor vessel is attractive in that the vortex action is capable of entraining particles in a stream around the inside perimeter of the vessel permitting control of the particle average residence time in this area of solar flux. This swirling stream of gas, when driven from tangential flow input in the lower part of a cylindrical cavity, would have an upward component of flow which would tend to carry entrained particles in that direction.

The solar chemical reactors studies up to now have invariably used transparent fused quartz windows, although this material is known to devitrify in the presence of water vapor at temperatures of about 900^{0} C (1700^{0} F) and higher. A further disadvantage of fused quartz is its poor resistance to abrasion. The material is comparatively soft. If it is used in an application where it will be abraded by harder materials, such as ash from coal, it will eventually appear to be lightly sandblasted on the abraded surface. This of course reduces the transmission of radiant energy.

The dominant criteria for the selection of transparent fused quartz window materials have been its excellent thermal shock resistance and good optical transmission. It is clear, however, that it has important deficiencies for this application.

C. Vortex Reactor Configuration

The vortex reactor model constructed during this program is shown in Figures 1 through 4. The reactor is composed of a reaction cylinder in which the standing vortex is generated and an ash collection cylinder which decreases the vortex maximum tangential velocity and the gas stream vertical velocity in order to separate the solid and gaseous reaction products; a closeup view of these parts is shown in Figure 2. Various flow manifolds are necessary for recirculating gases in order to maintain a stable vortex; closeup views of these are shown in Figures 3 and 4.

Two centrifugal fans are used, one to establish and maintain the standing vortex and the other to simulate the flow of a reactant gas into the system. The inlet manifold at the bottom of the reaction cylinder is mounted tangentially and is fitted with a flow control (damping) valve located immediately upstream of the manifold discharge point. A vertical tube is provided at the center of the ash collection cylinder for withdrawal of gaseous reaction products. Simulated solid-particle reactant material was introduced into the system through a small hopper positioned above a venturi section in the lower manifold. For this model, the lower end of the reaction cylinder consisted of an aluminum plate, although in a working solar reactor this plate would be a transparent window through which high-flux radiant energy would enter the reactor volume.

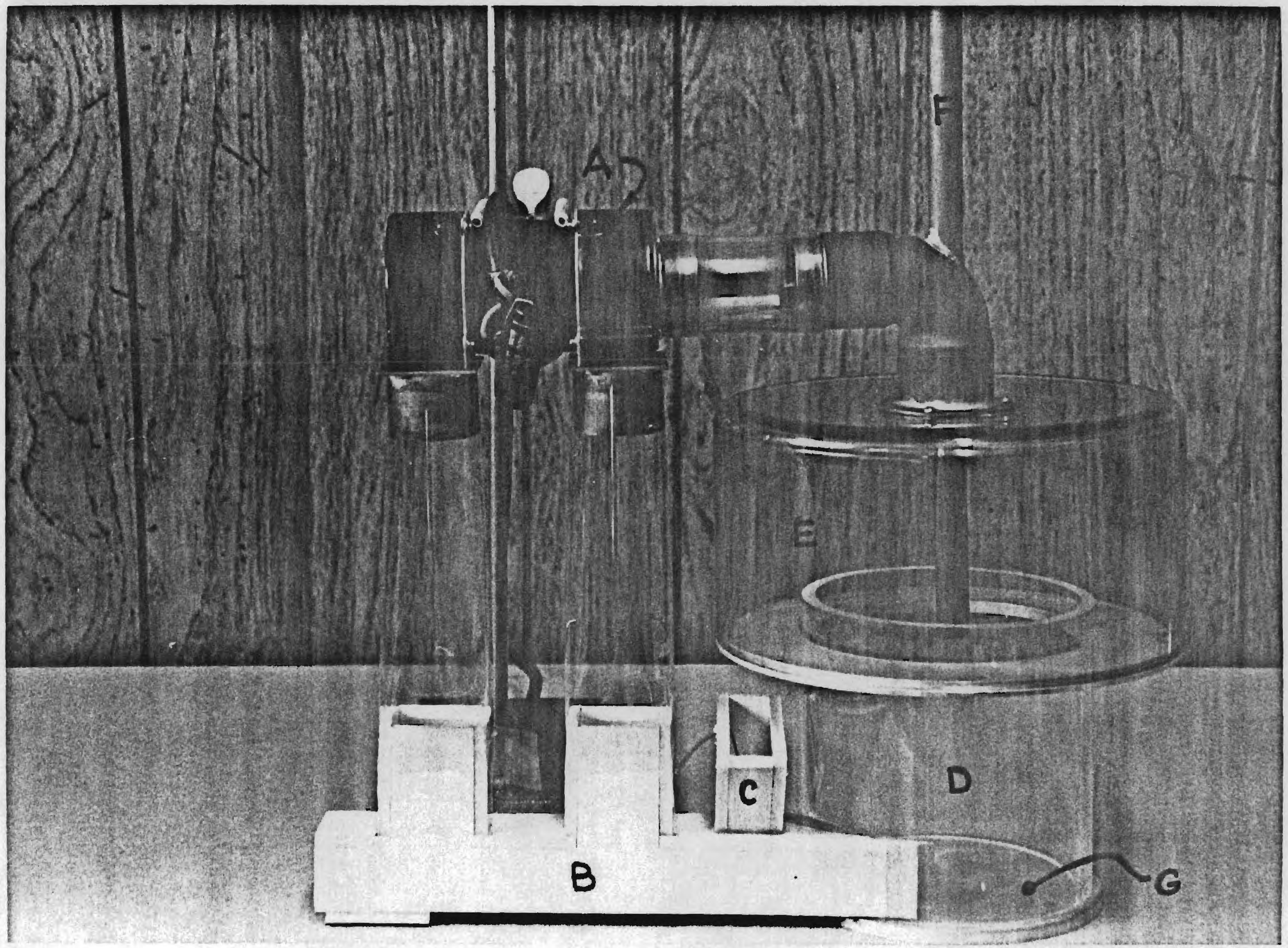

Figure 1. Vortex-Flow Reactor Model, showing General Arrangement:
a. Fans; b. Lower Manifold; c. Feed Hopper; d. Vortex Chamber;
e. Ash Chamber; f. Gas Discharge Tube; g. Aperture.

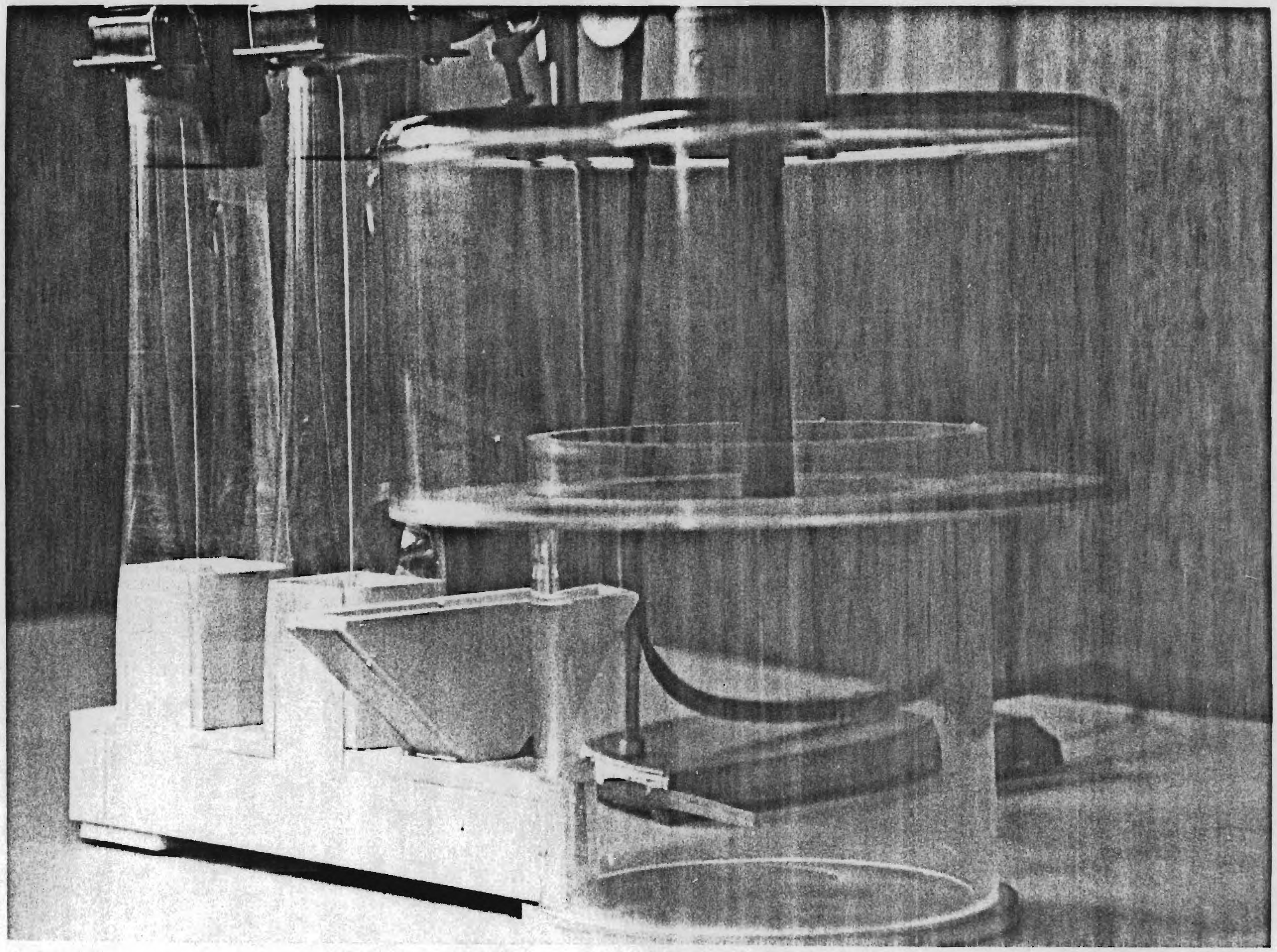

Figure 2. Closeup View of Vortex Chamber and Ash Chamber.

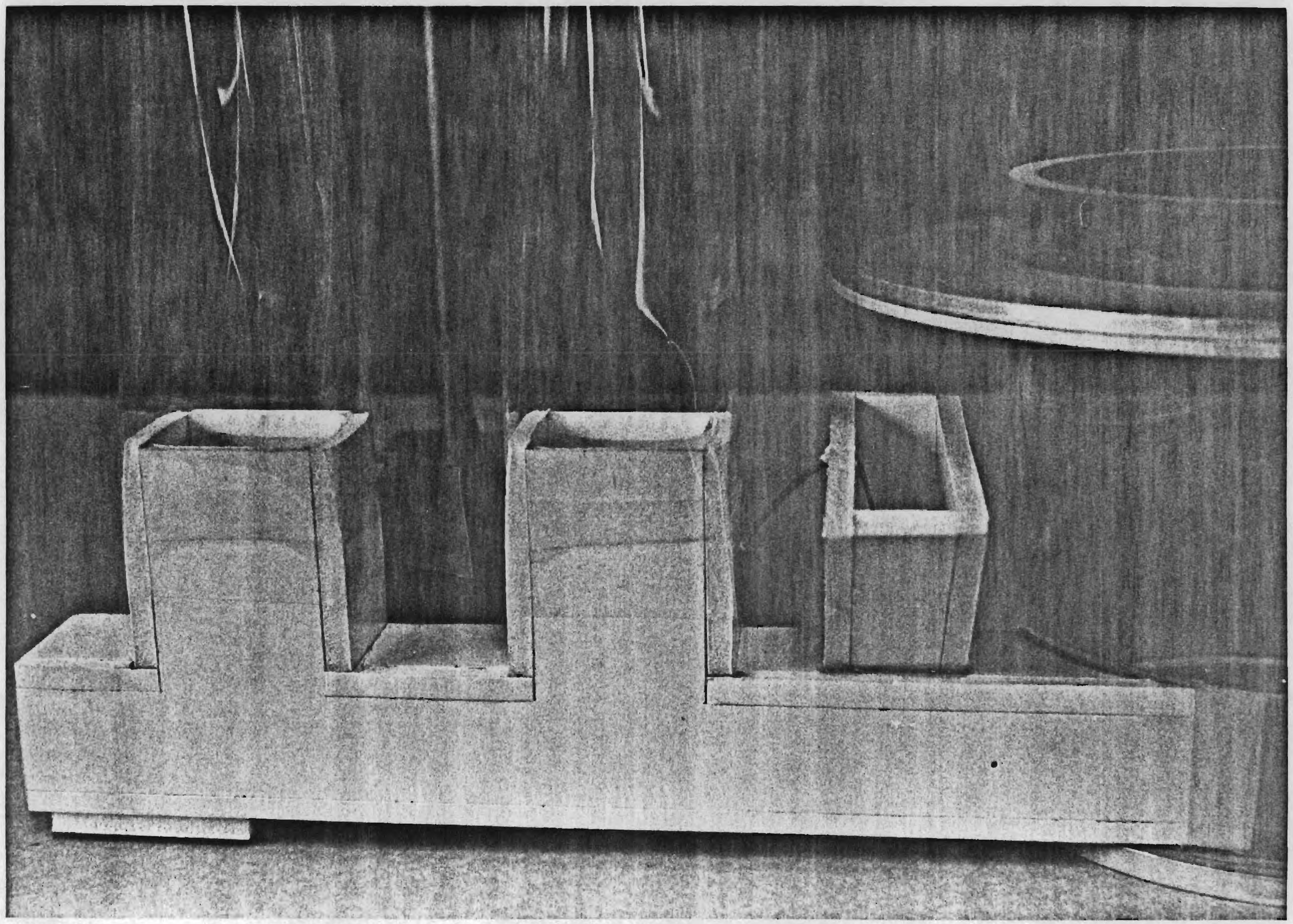

Figure 3. Inlet Manifold, with Reactant Gas Fan Inlet on Left, Vortex Fan Inlet in Center, and Feed Hopper on Right.

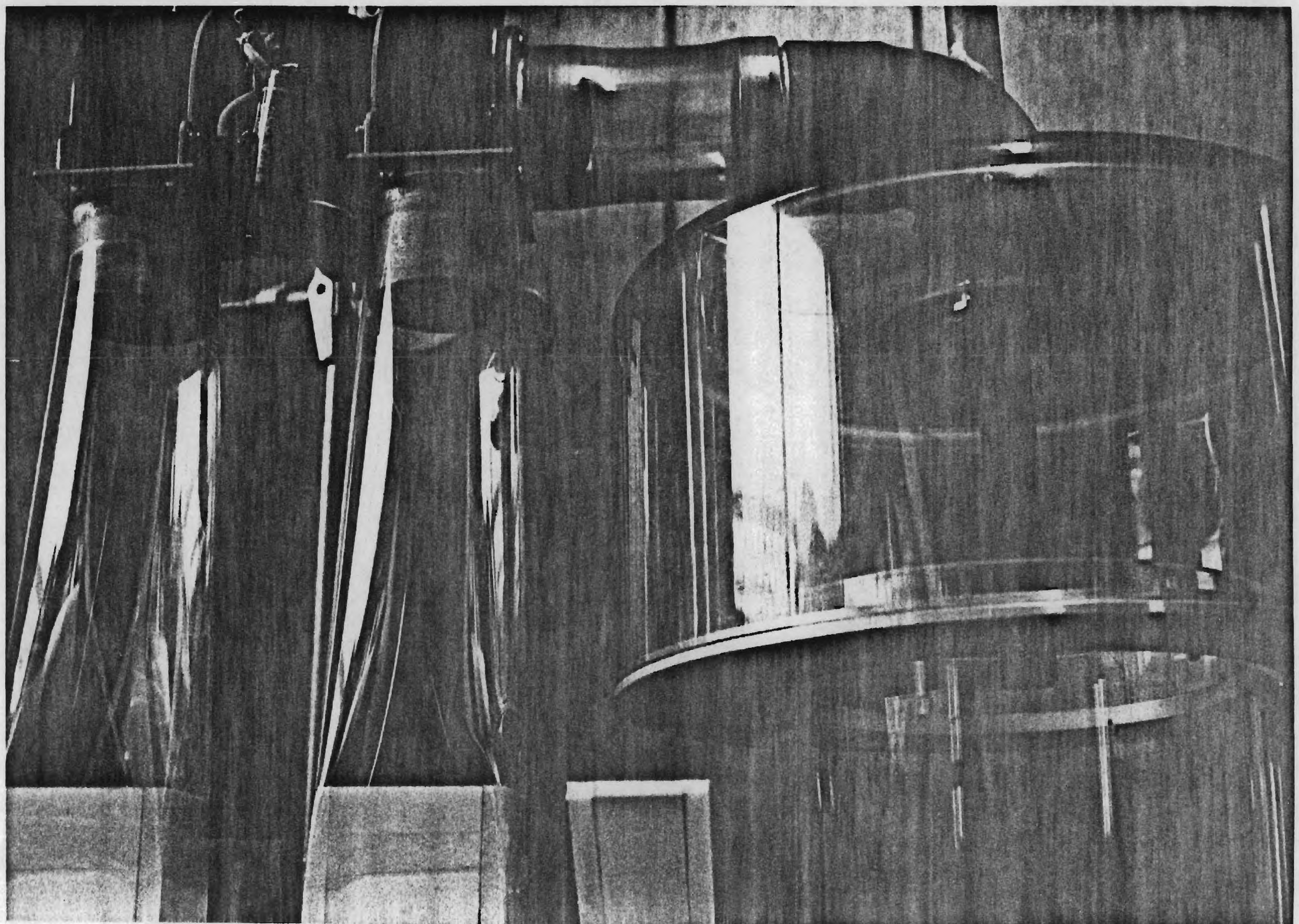

Figure 4. Vortex-Flow Reactor, shown from Below to Illustrate Ash Chamber Support Method.

D. Design Considerations

Sizing of the model reactor was based on minimizing the chance for problems in flow patterns arising during scale-up. Based on past testing experience at the Advanced Components Test Facility (ACTF), where hot testing of an operating vortex reactor is anticipated, the minimum size device that would provide meaningful data is in the 20 kWth range. Based on the current ACTF flux distribution, a 5-inch diameter aperture was chosen for the model. This dimension then governed the remaining reactor model design dimensions.

The particulate material used to simulate powdered reactant was a mixture of styrene foam beads. The beads varied in diameter from one to three millimeters and had a specific gravity of approximately 0.2. Terminal velocity calculations revealed that these test particles could be suspended in an air stream with a vertical velocity in the range of 0.6 to 1.2 meters per second (2 to 4 ft/s) over the existing bead diameter range.

Based on these data, a 10 cubic foot per minute (cfm) discharge centrifical fan was chosen to power the standing vortex. This fan output, when coupled with the additional 10 cfm reactant gas simulation fan discharge could provide a 0.73 meter per second (2.4 ft/s) vertical flow within the vortex cylinder. This flow was within the range required for operation of the device and would permit both simulated ash collection and equilibrium operation in which beads were suspended in vertical equilibrium in the vortex for observation of flow patterns.

Injection of the beads into the system (and likewise reactant particles into a hot system at scale-up) presented a problem. Injection upstream of the fan in a low pressure area would result in the particles passing through the fan rotor. The result would be probable rotor erosion and particulate build-up over a period of time. Injection of particles downstream of the fan tended to result in blow-back of the beads out of the hopper. In order to solve this problem a venturi throat was created at the particle feed discharge which locally dropped the fan discharge static pressure below ambient and permitted the injection of beads. Since particle flow rates in a hot reactor would be controlled by a device such as a screw feeder, it is envisioned that injection at a fixed venturi throat would be adequate, rather than incorporating a variable flow throat that responds to total flow rate into the vortex cylinder. Thus, reaction control during variations in solar flux would consist only of varying the reactant input rates.

A primary feature of this type of reactor is the particle density decrease as the individual particles undergo pyrolysis or gasification. If the system design parameters are selected carefully, low density reacted particles (ash) tend to be carried upward by the flow in the vortex cylinder, where these products are then thrown outward into the ash collection chamber. More dense, unreacted, particles having a greater terminal velocity, remain in the vortex and, therefore, in the area of high solar flux, until they experience the density decrease associated with the chemical reaction and are then carried upward to the ash chamber. In the operation of this cold model such a density change was simulated by the use of various sizes of foam beads with decreasing terminal velocities as size decreased.

E. Vortex Reactor Model Construction

The model constructed for this project was made using as much transparent material as possible in order to permit visual and photographic observation of system flow phenomena during operation. The 5-inch diameter vortex cylinder as well as the $8\frac{1}{2}$-inch diameter ash collection chamber were fabricated from $\frac{1}{4}$-inch thick clear plastic as shown in Figure 5. The fan discharge ducts were fabricated from thin polycarbonate sheet and the fan suction duct was a short section of clear plastic tubing.

The lower fan discharge manifold, particle injection hopper, damper valve, and venturi were constructed from $\frac{1}{4}$-inch foam board using contact cement and edge reinforcements as shown in Figure 6. Commercially available copper tube fittings were used in combination with brass sheeting to construct the fan and ash chamber adaptors.

The fan employed was a dual rotor, Rotron model number 57845 from Rotron Manufacturing Co., Woodstock, N. J. rated at 20 cfm at 3500 rpm.

F. Design Analysis

Two types of vortex motion are described in the literature of fluid flow (Ref. 1,2). One of these is the solid-body type (or wheel type) of angular motion about an axis, in which individual particles maintain their relative positions as in the case of a rigid solid. For this case, the velocity of a particle moving along a circular streamline is:

$$V = \Omega r \qquad (1)$$

where: V = particle velocity

Ω = angular velocity of the vortex about its origin

r = radius of the streamline

The circulation along any circular streamline of radius r, is defined as the line integral of the velocity around the streamline:

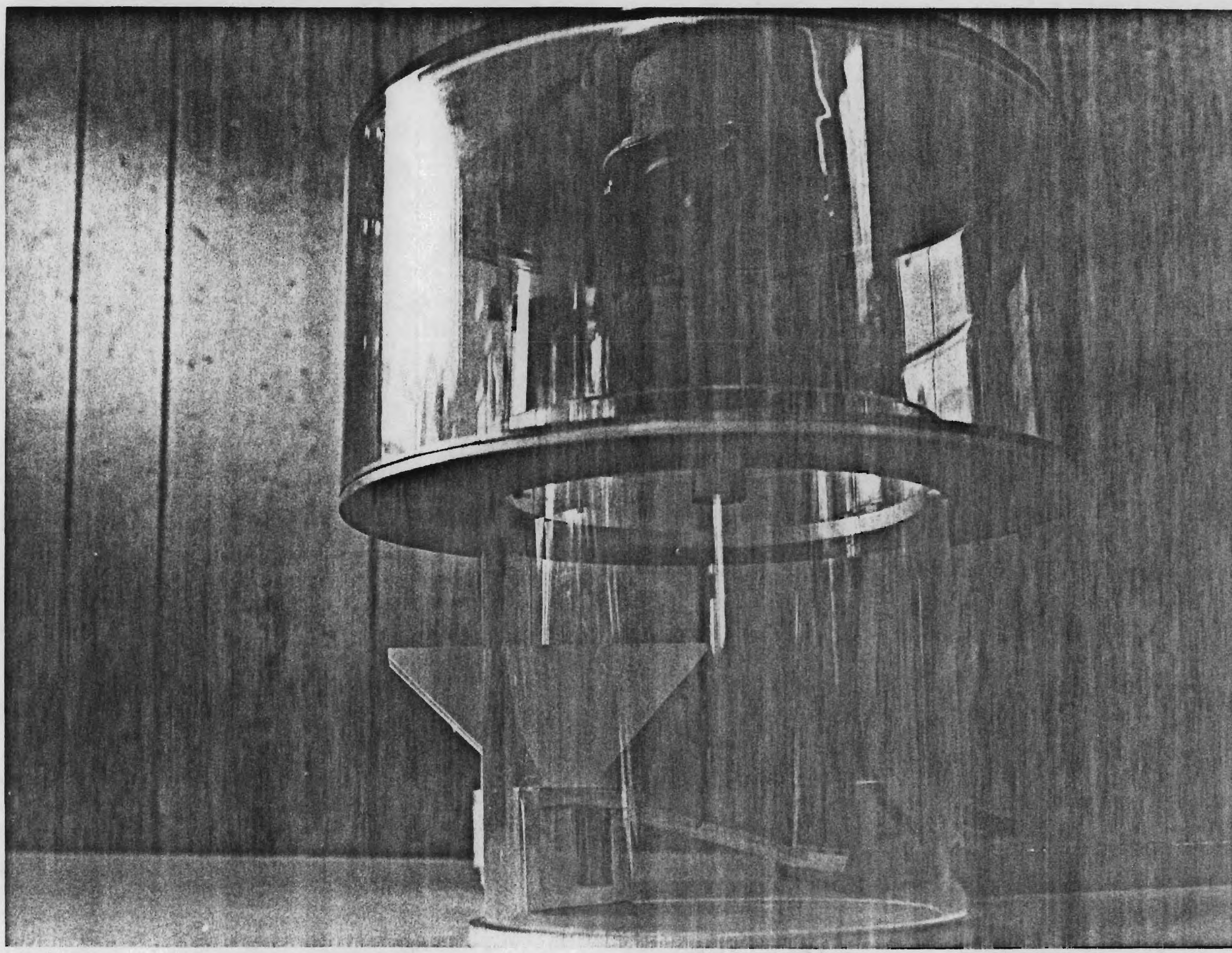

Figure 5. End View of Reactor Chambers showing Tangential Entry of Fan Manifold into Vortex Chamber at Lower Left.

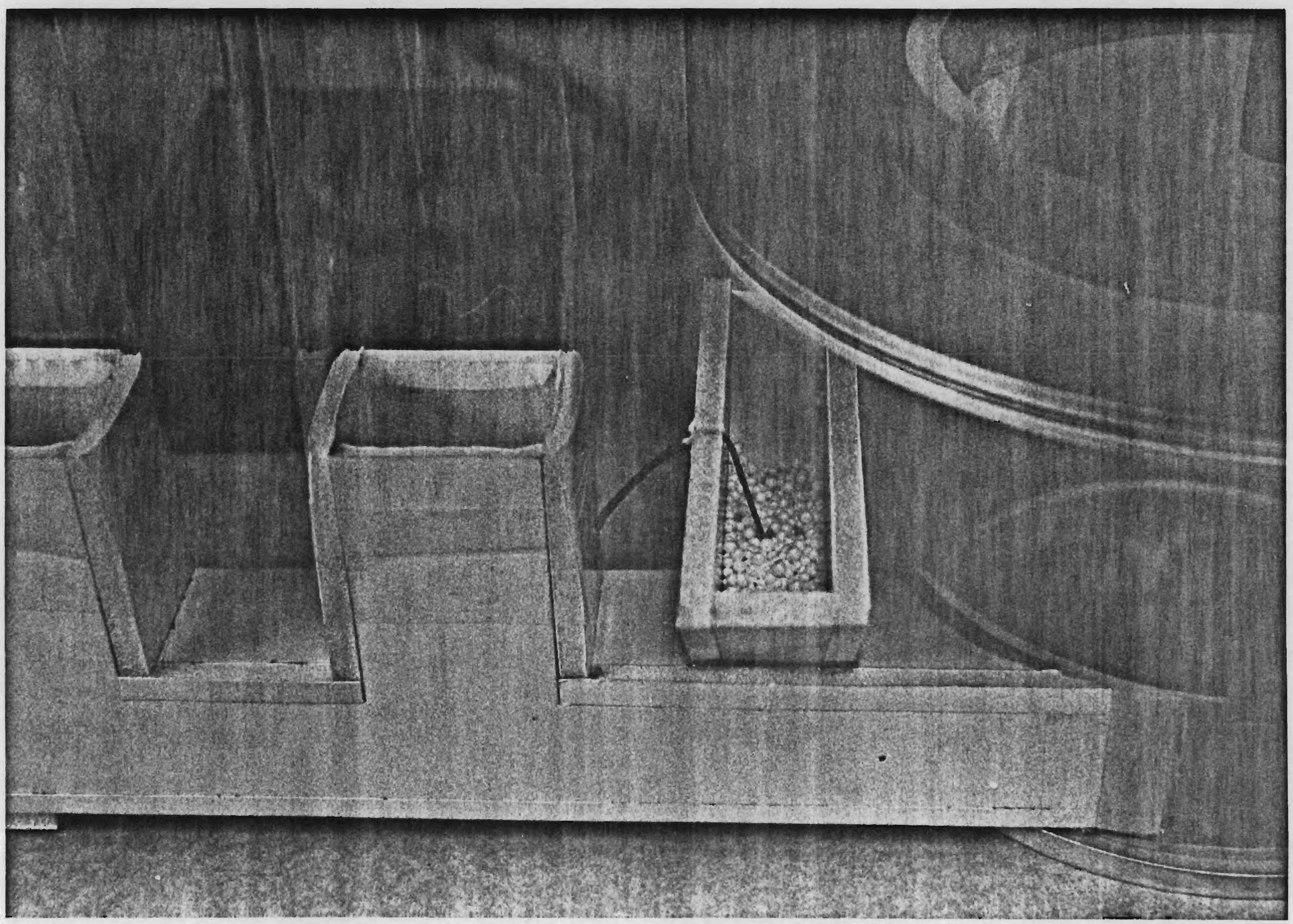

Figure 6. View of Feed Hopper charged with Foam Beads prior to Startup.

$$\Gamma = \int_0^{2\pi} Vr \, d\theta = \Omega r^2 \int_0^{2\pi} d\theta = 2\pi\Omega r^2 \qquad (2)$$

where: Γ = circulation, as defined above.

It is seen in equation (1) that the particle velocity is directly proportional to the radius of the streamline and that the particle velocity approaches zero at the center of the vortex. One example of the solid-body vortex is the motion of a fluid in a rotating container, after steady state has been attained.

The second type of vortex is the classical vortex, also called by various other names such as the free vortex, the potential vortex, and the standing vortex. This case describes approximately the motion in tornadoes and whirlpools, and more closely matches the conditions in the vortex-flow reactor. As before, the streamlines form concentric circles, but in a classical vortex the tangential velocity along any streamline is inversely proportional to the radius of the streamline:

$$Vr = K \qquad (3)$$

where K is a constant. It can be shown that the circulation around a fluid element not enclosing the origin of the vortex is zero. That is, the fluid motion is irrotational even though the fluid particles follow circular paths. If a cork is floated in a pan of water in which the water moves as in a classical vortex, the cork will travel in circles but with a purely rectilinear motion; the cork has zero angular velocity. The circulation along a streamline enclosing the origin of the vortex is defined as in equation (2), the line integral of the velocity around the streamline:

$$\Gamma = \int_0^{2\pi} Vr \, d\theta = K \int_0^{2\pi} d\theta = 2\pi K \tag{4}$$

Substituting equation (3) into equation (4), we can express the circulation in terms of the particle velocity and streamline radius:

$$\Gamma = 2\pi Vr \tag{5}$$

It is seen in equation (3) that the particle velocity is inversely proportional to the radius of the streamline and that the particle velocity approaches infinity at the center of the vortex. The solid-body vortex and the classical vortex are "ideal" cases, and actual vortices have a behavior intermediate between these two extremes.

By injecting a three-millimeter diameter single foam bead into the vortex chamber of the reactor model and recording the time required to complete 100 revolutions, an approximate tangential velocity was determined of 4.5 feet per second. Using this value and equation (5), we obtain a value for the circulation Γ, of 5.9 square feet per second.

Since the vortex existing in the reactor model conforms approximately to the classical case, the tangential velocity distribution can be estimated using equation (5) and the known value for Γ. This distribution across the radius of the vortex chamber is as follows:

RADIUS (inches)	½	1	1½	2	2½
VELOCITY (ft/s)	22.4	11.2	7.5	5.6	4.5

Vertical Velocity

The vertical component of the flow inside the vortex chamber is given by the average volume flow rate divided by the cross-sectional area:

$$V_v = \frac{Q}{A}$$

$$Q = 20 \text{ cfm}$$

$$A = 0.136 \text{ ft}^2$$

$$V_v = 2.4 \text{ ft/s (vertical velocity)}$$

Average Falling Bead Velocity

Approximate time to fall 6 ft in 70^{0} air:

Dia	Time
1 mm -	½ s
2 mm -	2¼ s
3 mm -	3 s

Particle Residence Time in Solar Flux

Net vertical velocity at 20 cfm fan discharge:

Dia	V_v net
1 mm -	0.44 ft/s (upward)
2 mm -	∿0 (equilibrium)
3 mm -	- 1.56 ft/s

where residence time for small particles (simulated reacted particles) in the 5½ inches high vortex chamber is approximately 1 second minimum.

G. Testing

The reactor model was operated in several configurations. Initial operation took place with the reactant simulation fan suction port blocked and beads placed in the vortex chamber prior to fan start. During operation in this configuration the system stabilized as prediced with the small beads carried upward to the ash chamber, the intermediate beads circulating in vertical equilibrium around the wall of the vortex chamber and some large beads circulating on the lens simulator, as shown in Figure 7. During operation the damper valve was adjusted to give maximum vortex velocity while maintaining vertical velocity. It was found that vertical velocity was rather insensitive to small damper valve adjustments so that vortex tangential velocity could be maximized without noticeable back-pressuring of the fan. It was noted that flow variations in the upward spiraling air stream of the vortex caused bead capturing at various levels in the vortex cylinder. These levels of capture tended to correspond to bead size with the smaller beads rising to the upper wall of the chamber as would be expected from the analysis.

The next set of runs involved the evaluation of the system with the reactant simulator fan in operation. Since the vortex fan system recirculates, the system is closed (except for a small amount of leakage) when the reactant fan is starved. Smoke tests verified flow out of the reaction products withdrawal tube as the reactant fan was operated. This activity was predominantly a test of system leakage because the inlet of the reaction products discharge tube is located in the center of the vortex and, therefore, in a relatively low pressure area. During this series of runs, the damper valve was again adjusted to provide optimum vertical versus tangential flow velocities in the vortex chamber using beads inside the system before start up.

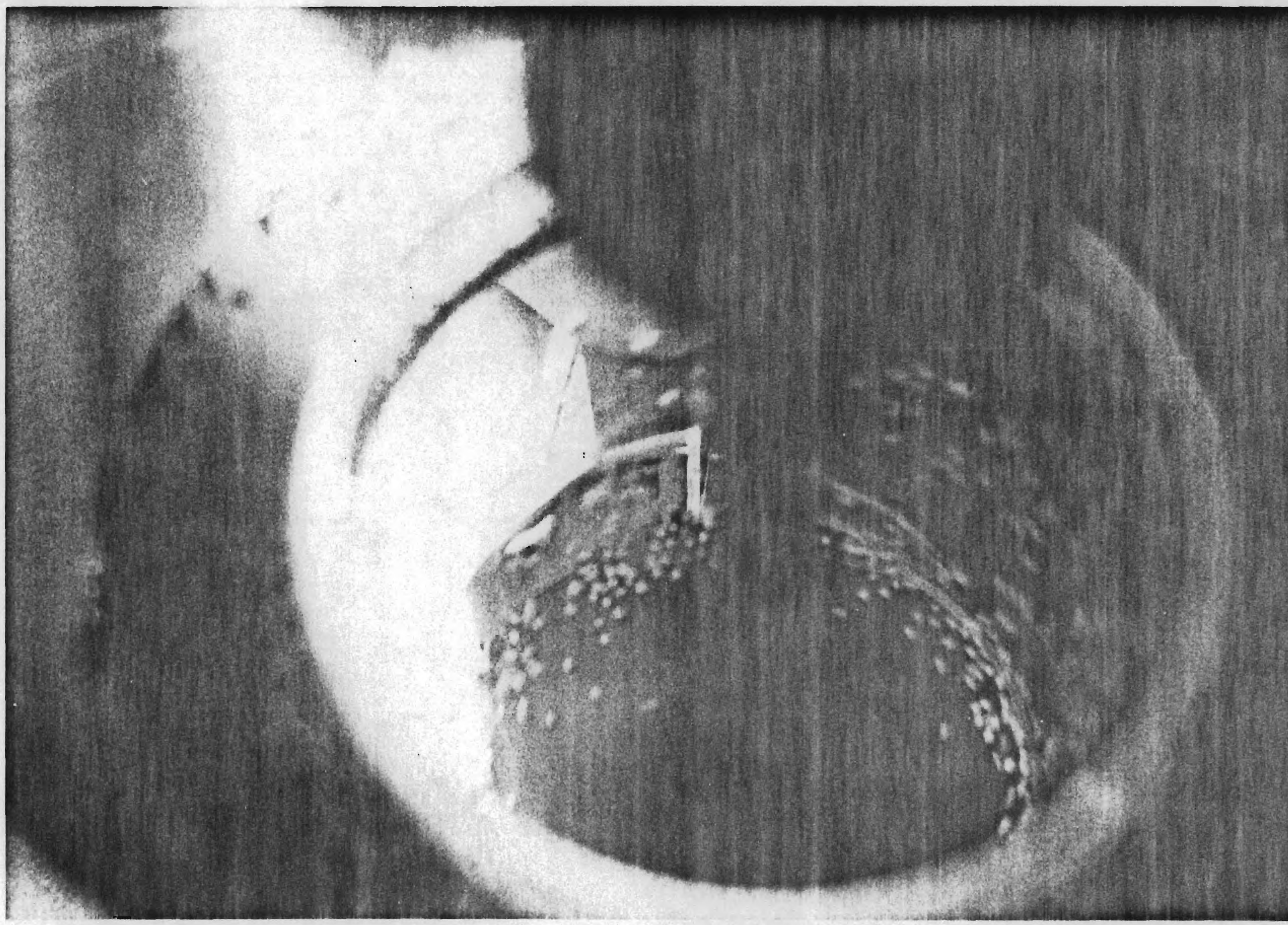

Figure 7. View of Vortex Chamber Looking Downward showing Distribution of Larger Beads around "Window" Plate. (Note tangential fan air input at left.)

The last run series involved the use of the feed hopper to inject simulated feed-stock (beads) to evaluate steady state operation; the changed feed hopper was shown in Figure 6. A small door in the bottom of the hopper was opened allowing ambient air to enter the recirculation system, carrying in beads from the hopper. The smallest of the beads were immediately passed through the vortex chamber and deposited in the ash chamber, as shown in Figures 8 through 10. Intermediate sized beads were generally suspended in the vortex at varying heights up the chamber wall according to size. Continued observation of the system in operation revealed that, probably through a series of collisions between particles, some of the larger beads were periodically discharged into the ash chamber. No particles were recirculated into the vortex fan during any of the test series, verifying the proper location of the fan suction port in the ash chamber.

H. Test Conclusions

- The bench model reactor operated as predicted by preliminary calculations.

- No carry-over of reactant particles into the vortex fan was observed.

- Visual observation of the reactor operating characteristics indicate excellent flow stability and good segregation of reactant particles by density.

- The model characteristics are predictable and therefore, the system appears to be easily scalable.

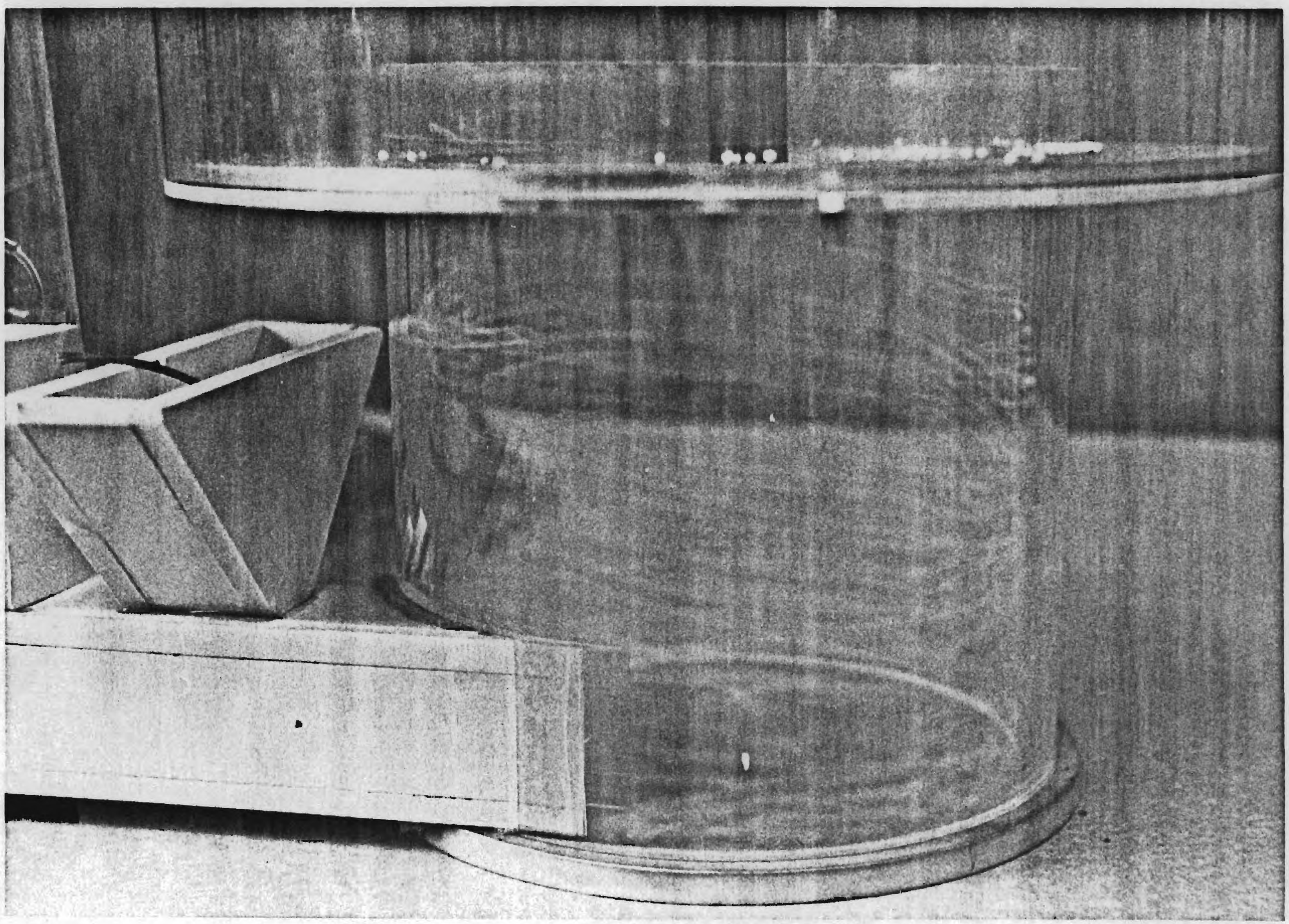

Figure 8. View of Chambers with System in Operation. (Note bead circulation in vortex chamber and "ash" beads in upper cylinder.)

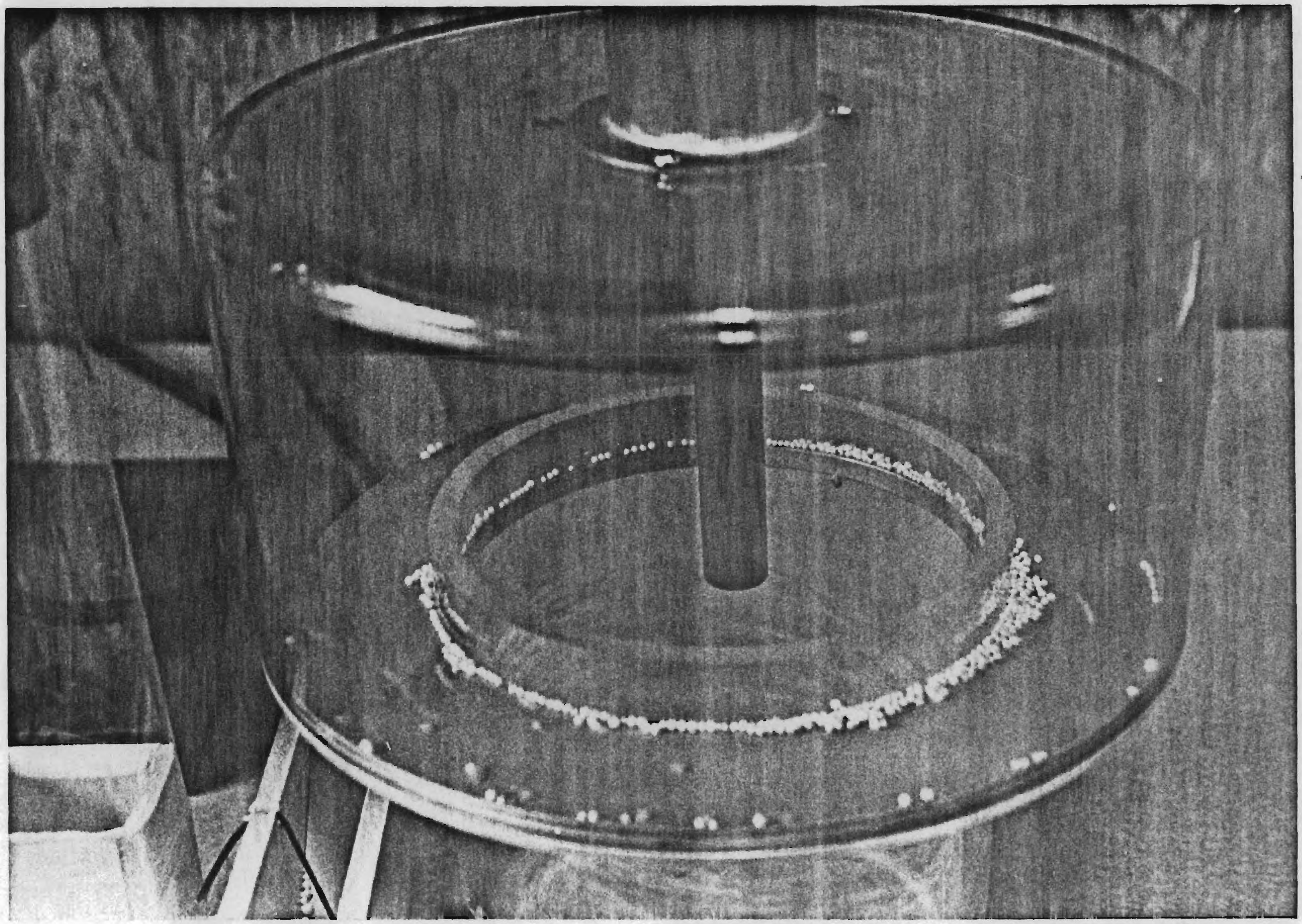

Figure 9. View from Above showing Distribution of Beads Discharged to Ash Chamber.

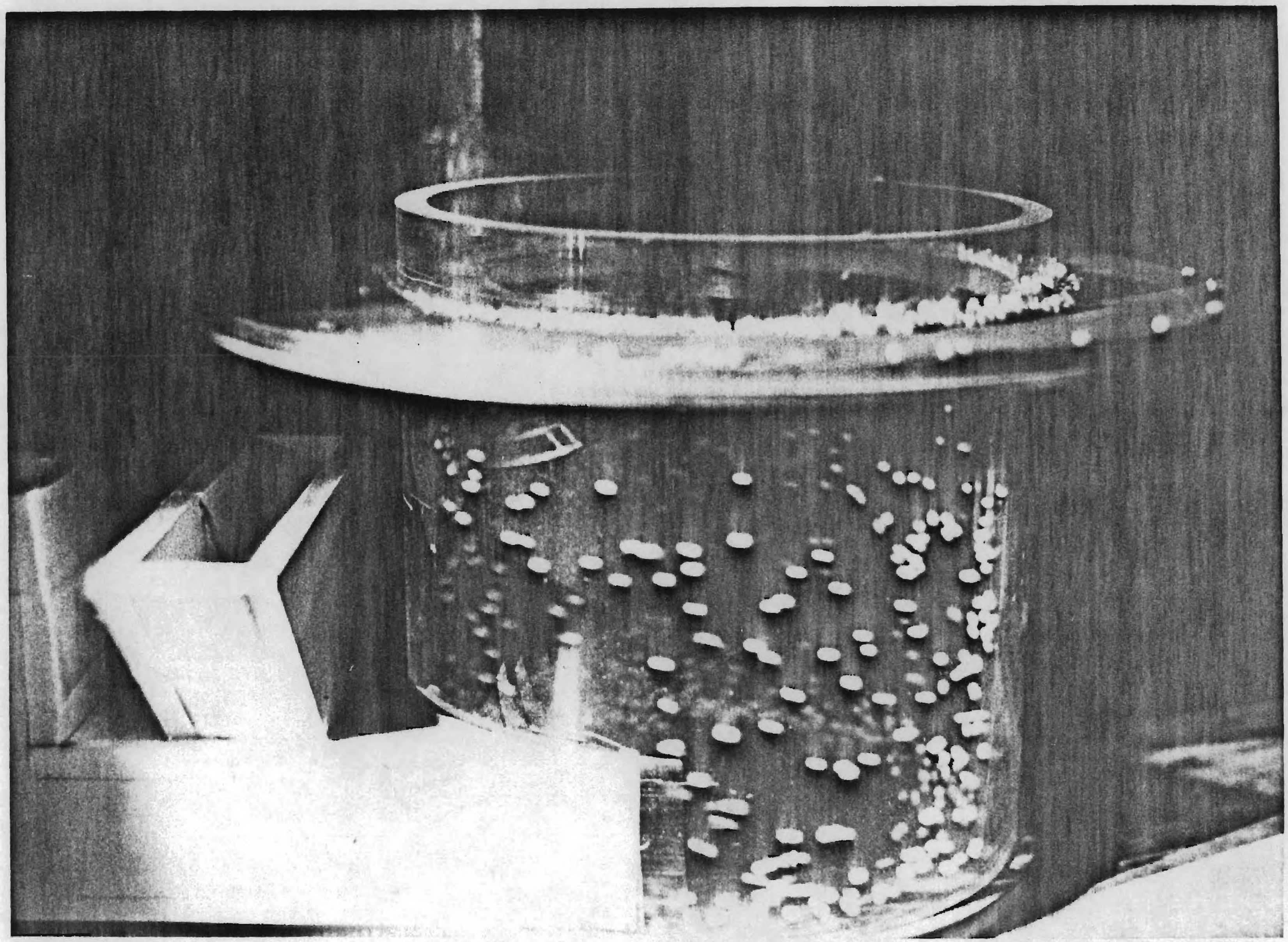

Figure 10. View showing Stop-Action Distribution of Beads in Vortex Chamber during System Operation.

I. Preliminary Design of a Vortex-Flow Reactor

Figure 11 is a preliminary design drawing of a vortex-flow reactor sized for testing at the ACTF. The model tests conducted on this program have demonstrated that satisfactory particle flow profiles and residence times can be obtained with a six-inch diameter vortex chamber and a chamber length-to-diameter ratio on the order of one to two. The reactor vortex chamber will accept about 23 kW of thermal power through the aperture with the present ACTF flux distribution. This power level will allow relatively easy measurement of reactant flows while minimizing cost of the experimental apparatus. Thus, the vortex chamber dimensions have been established at six inches diameter by approximately ten inches height.

The model tests further established that an ash collection chamber diameter of about ten inches is satisfactory to achieve good ash separation. Other dimensions are less critical, although the fan circulation piping should be kept relatively compact in order to minimize pressure drops and heat losses. Several improvements in apparatus arrangement have resulted from experience gained during operation of the bench model reactor. Among these is the incorporation of a canted lower closure door into the ash chamber design. Location of the ash removal door at the low point in this closure will permit the periodic removal of residue from the assembly and will permit continuous operation rather than batch processing, if desired. An observation window has been included in the ash collection cylinder to allow visual inspection of flow rate control, ash collection performance, and ash level.

The reactor will operate in the temperature range up to 2000° F and, therefore, must be constructed of a high-strength alloy. Inconel 718 has

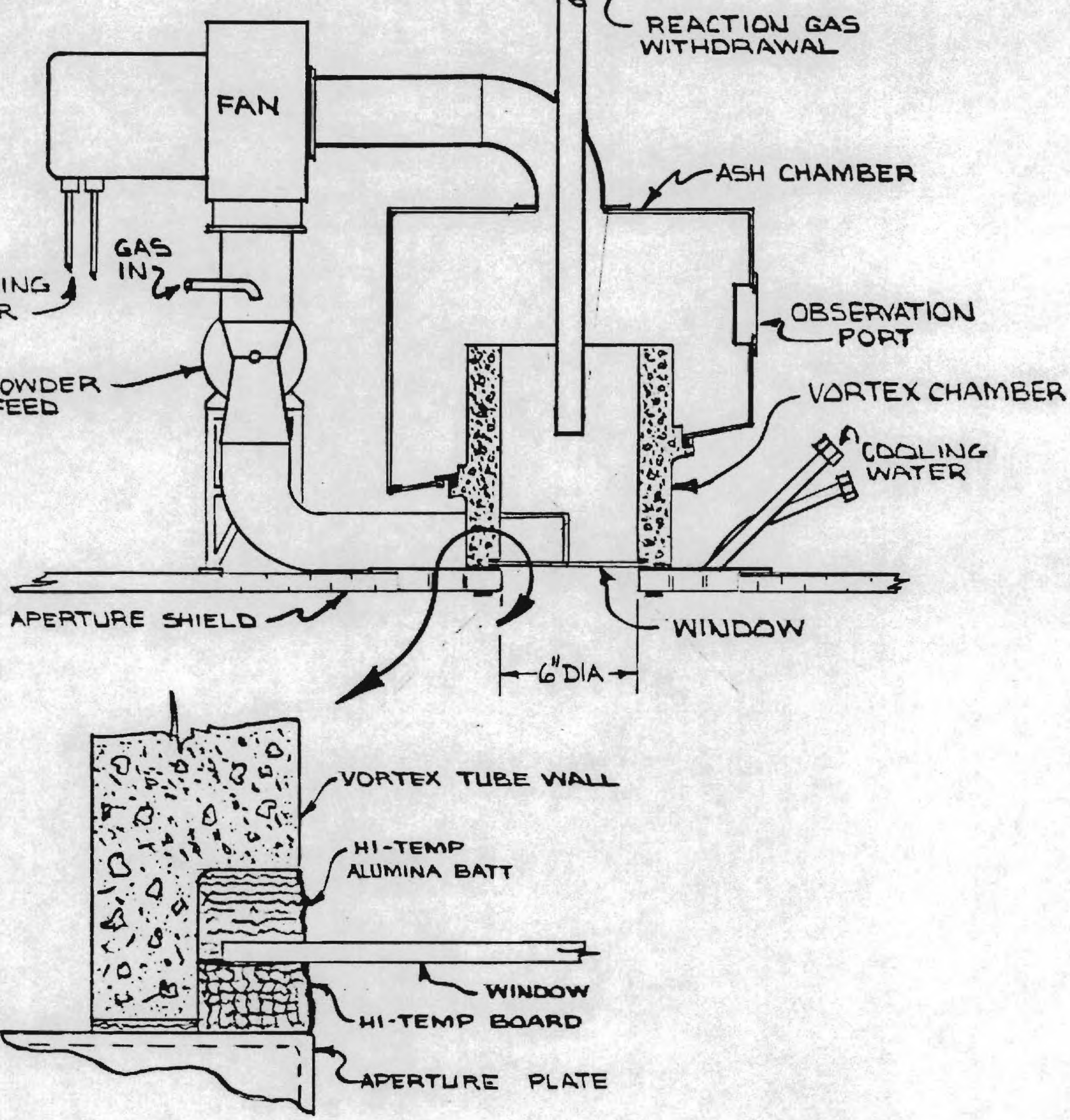

Figure 11. Preliminary Design - Vortex Reactor, 25 kWth.

been chosen for construction of the ash chamber and manifolds because of its good high-temperature mechanical properties combined with its relatively good availability and moderate cost.

The vortex chamber wall will be made from a one-piece casting of a castable ceramic material, Greencast-97-L, manufactured by the A. P. Green Corporation of Mexico, Missouri. This is a high-alumina material, capable of withstanding temperatures up to 3300^{0} F. It has good insulating properties, resistance to carbon monoxide, is readily available and inexpensive. Previous testing at the ACTF has shown that this castable is not likely to suffer thermal shock cracking during transients in radiant input power. Its use for the vortex chamber wall will permit incorporation of an integral ash chamber support flange and window mating step, as shown in Figure 11.

The high-temperature fan assembly selected is a 7½-inch Design 2000 unit, manufactured by the Garden City Fan and Blower Company of Niles, Michigan. It is capable of operating at 1000 revolutions per minute at working temperatures up to 2000^{0} F. It is rated to deliver 546 CFM, which is several times the flow rate required for this experiment. The fan will be driven by a variable-speed motor in order to permit optimization of reactant particle residence time in the vortex chamber.

The preferred window material is Vistal, a low-porosity polycrystalline alumina manufactured by Coors Porcelain Company of Golden, Colorado. This material is identical to Lucalox, developed by the General Electric Company and subsequently licensed to Coors. It is reported that Vistal is available in sheets up to 5 by 8 inches in dimensions, from which a six-inch circular window could be cut with two flat edges; its use would require modification of the window mounting structure of the vortex chamber but would not seriously affect the power input through the reactor aperture. Vistal is translucent, rather than transparent, but is capable of use at temperatures approaching 3000^{o} F. The second-choice window material is transparent fused quartz.

The vortex-flow reactor will be fully instrumented with thermocouples for determination of system temperatures at critical positions. Fan flow rates will be calculated, based on revolutions per minute and system pressure drop. Solid reactant flow rates will be determined by weight measurements, reactant gas flow rates will be measured by conventional rotameters, and incident solar power will be measured by an array of water-cooled calorimeters surrounding the reactor aperture, coupled with flux maps determined using the ACTF flux-scanning system.

Test Program

The vortex reactor will be tested for approximately 30 hours at the focal zone of the Advanced Components Test Facility. During the test the operating characteristics of the system will be fully explored. Fan flow rates vs internal temperature will be investigated during preliminary testing. Once operating regimes are established, carbon particles and carbon dioxide will be introduced into the system in order to determine optimum operating parameters for the production of carbon monoxide. Approximately 10 hours of testing will be conducted under varying solar flux conditions in order to characterize operation during cloud transients.

At the conclusion of testing an analysis will be undertaken to quantify results of operation over a range of temperatures up to 2000^{o} F. Analysis will include a determination of temperature stability, equilibrium predictability and thermal loss mechanism. The analysis and reporting will be done in such a way as to be of maximum value to other organizations desiring to develop vortex type receiver systems.

Cost and Schedule

It is estimated that the program from detail design through final report publication will cost approximately $55,000 total including approximately $27,000 personel services, and $5,000 for construction materials. Some instrumentation currently on hand at Georgia Tech will be used for temperature and solar flux measurement.

The construction and test program will be completed over a five month period beginning in April 1982 and including approximately three weeks of testing at the ACTF in July 1982. This July test window is currently open at the ACTF and testing during this period will characteristically permit transient operations mentioned above as well as steady state elevation of the system.

J. Recommendations

The concept of a vortex flow reactor for solar thermal chemical conversion is sound, appears to be relatively inexpensive and overcomes problems associated with other types of reactor equipment. This system is scalable, capable of steady-state operation and should be very reliable. The particle density segregation feature of the system minimizes control problems and makes the device highly tolerant of varying input radiant flux.

It is recommended that a 25 kWth experimental vortex-flow reactor system be constructed and tested at the DOE ACTF to fully characterize the device at operating temperatures up to 2000^{o} F.

It is currently anticipated that construction and testing of the vortex-flow reactor will be conducted as a task under the DOE-sponsored Solar Thermal Advanced Research Center contract at Georgia Tech.

REFERENCES

1. Ascher H. Shapiro, The Dynamics and Thermodynamics of Compressible Fluid Flow, Volume I, The Ronald Press Company, New York, 1953, pp. 267-273.

2. R. B. Bird, W. E. Stewart, and E. N. Lightfoot, Transport Phenomena, John Wiley and Sons, Inc., New York, 1960, pp. 96-98, 108-111, 133-140, 149.